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Industrial Symbiosis Potential of the Sines oil refinery – environmental and economic evaluation

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Para a minha mãe,

Obrigado por tudo

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Resumo

As simbioses industriais são um ramo da ecologia industrial, e consistem numa abordagem colaborativa entre diferentes indústrias e empresas que visam melhorar o seu desempenho ambiental e económico e que envolve a troca de resíduos / subprodutos como substitutos de matérias-primas. Esta colaboração é condicionada pela proximidade geográfica entre as indústrias e pode enfrentar alguns entraves ao seu desenvolvimento como barreiras informativas, económicas, motivacionais ou políticas.

O objetivo principal desta tese foi desenvolver uma metodologia que permitisse encontrar e avaliar novas simbioses industriais e aplicá-la ao caso de estudo da refinaria de Sines. A metodologia foi dividido em quatro fases. A primeira fase é a fase em que, por avaliação de casos de estudo similares, as potenciais sinergias são encontradas. A segunda foi feita com base numa revisão de literatura referente às principais barreiras para o desenvolvimento de simbioses industriais. Esta fase foi desenvolvida para filtrar rapidamente as potenciais sinergias que enfrentassem entraves ao seu desenvolvimento. As outras duas fases só foram aplicadas às potenciais sinergias que passaram com sucesso a referida filtragem. Essas fases consistiram numa avaliação ambiental através de uma análise de ciclo de vida e de uma análise financeira.

A aplicação da metodologia mostrou duas novas potenciais sinergias para a refinaria de Sines. Os resultados da avaliação dessas potenciais sinergias foram muito promissores, tanto ambientalmente como financeiramente. Esta pesquisa demonstrou, assim, o potencial e os benefícios associados ao desenvolvimento de simbioses industriais, se as barreiras para este desenvolvimento forem ultrapassadas com sucesso.

Palavras-chave: Simbioses Industriais; Ecologia Industrial; Refinarias; *Screening*; Análise Ciclo de Vida; Análise Financeira.

Abstract

Industrial symbiosis is an application of industrial ecology that consists of a collaborative approach between different industries and firms aimed at improving their environmental and economic performance involving the exchange of waste/byproducts as substitutes for raw materials. This collaboration is conditioned by the geographic proximity between industries and may face some information, economic, regulatory or motivational barriers.

The main objective of this thesis was to develop a methodology to find and evaluate new potential exchanges in light of industrial symbiosis and to apply it to Sines oil refinery case study. The methodology was divided into four phases. The first phase is where, through the analysis of similar case studies, the potential new exchanges are uncovered.The second was made based on a literature review on the main barriers to industrial symbiosis development. This phase was developed to swiftly filter potential synergies that would face barriers to its development. The other two phases were only applied to the potential synergies that successfully passed the “filter”. Those phases consisted of an environmental evaluation through a LCA and a financial analysis.

The application of the methodology showed two new potential synergetic possibilities for the Sines oil refinery. The results of the evaluation of those potential synergies were very promising both environmentally and financially. This research thus demonstrates the potential and benefits associated with the development of industrial symbiosis networks if the barriers to this development can be successfully surpassed.

Keywords: Industrial Symbiosis; Industrial Ecology; Refineries; Screening; Life Cycle Analysis; Financial Analysis.

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Acronyms and abbreviations

CECP – Centre of Excellence in Cleaner Production

GDG – Grangemouth Development Group

GDP – Gross Domestic Product

GHG – Greenhouse Gases

IE – Industrial Ecology

IRR – Internal Rate of Return

IS – Industrial Symbiosis

LCA – Life Cycle Analysis

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment MDEA – Methyl Diethyl Amine

NISP – National Industrial Symbiosis Programme

NPV – Net Present Value

PREPA – Puerto Rico Electric Power Authority

QF – Qualifying Facility

UK – United Kingdom

CHAPTER 1: INTRODUCTION AND THESIS OUTLINE

1.1. Introduction

Since the publication of the *Brundtland Report,* in 1987 (WCED, 1987), the term 'sustainable development' became widely spread and is nowadays used on numerous occasions. In order to account for sustainable development, as it was defined on the *Brundtland Report*, one should take in consideration social and environmental aspects of corporate activity in addition to the economic ones (Bebbington, 2001).

Industrial ecology (IE) was refered to as the *"science of sustainability"* by Allenby (1999) and emerged as a multidisciplinary field that recognizes this interdependence between multiple different areas (Allenby, 2006). IE aims at providing guidelines for a closer relation between development and sustainability (Costa, 2011). This field of study started to get more attention in 1989, after the publishing of Frosh and Gallopoulos article *Strategies for Manufacturing* (Agarwal, 2011), where the authors conceptualised IE as an holistic approach to achieve the proper balance between economic benefits and environmental needs. Even though the expression "industrial ecology" may, at first, seem a contradiction for linking industry and ecosystems, it explores the opposite assumption on which industrial systems can be viewed as a type of ecosystem (Erkman, 1997). This assumption comes in line with Jelinski et al. (1992) argument that "an industrial system must be viewed not in isolation from its surrounding systems, but in concert with them".

Industrial symbiosis (IS) is, perhaps, the best known application of industrial ecology (Centre of Excellence in Cleaner Production, 2007). Several definitions for IS can be found in the literature, the most known was introduced by Chertow (2000), which stated that *"Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity"*. The common saying "One man's trash is another man's treasure" may be used for a simple explanation of the IS concept, a by-product or waste of an industry may be considered a valuable input to another industry. However, it is important to note that IS does not solely refers to physical exchanges.

In IS, this cooperation between separate industries can bring economic, environmental and social benefits. IS networks have the potential to reduce inputs and raise resource productivity bringing more economic gain with less environmental impacts, while creating more employment opportunities (Ehrenfeld & Gertler., 1997; Mirata, 2004). IS can also have a role to play on a major environmental problem, global warming. Data from IS networks shows that IS exchanges can help fighting global warming through direct and indirect reductions in greenhouse gases (GHG) emissions (Harris S. , 2007).

Despite all the IS potential, the concept is still not widely spread across industries and companies, particularly in the Portuguese context. This fact was a major motivation for this thesis even more due to the current Portuguese economic context. Currently Portugal is losing industrial activity and companies everyday due to a reduction of economic activity and along with it go many jobs that are being lost as well. IS due to its potential in lowering production costs may create and/or save additional jobs allowing industries to generate more wealth while achieving a better environmental performance.

Even though it is already possible to find some documented cases where the IS concept is successfully applied there is still yet to appear a standard generalized methodology to find and evaluate potential new symbiosis. With this fact in mind, and acknowledging that there are some computer software programs based on input-output matching to assist in finding future potential IS networks, the author developed a methodology to find and evaluate new potential symbiosis, with this evaluation being both financial and environmental.

1.2. Thesis outline

The main goal of this thesis is to develop a methodology to find and evaluate new potential exchanges ("kernels") in light of IS. The case study selected for the development of this thesis was an oil refinery, owned by Galp Energia, situated in the Sines industrial area. The selection of this case study was due to the fact that petrochemical complexes are usual suspects for the development of IS networks and the fact that the refinery can be seen as an anchor industry since it is a heavy industry that deals with large quantities of material flows.

The thesis will include the following:

- **Chapter 1**: Brief introduction to the subject of IS and the motivation and goal of this thesis followed by the thesis outline.

- **Chapter 2:** A literature review of the barriers to IS and international IS case studies that include oil refineries.

- **Chapter 3:** Development of a methodology for the discovery of new potential exchanges including the Sines refinery that will allow a quick positive or negative feedback when considering an exchange. Development of a methodology for an environmental analysis, through a life cycle assessment, and a financial analysis of the exchanges.

- **Chapter 4:** Presentation of the case study.

- **Chapter 5:** Application of the methodology for the Sines refinery case study, including an environmental analysis, through a life cycle assessment, and a financial analysis of the exchanges with a previous positive feedback followed by a discussion of the results obtained.

- **Chapter 6:** Conclusions and recommendations.

CHAPTER 2: INDUSTRIAL SYMBIOSIS IN OIL REFINERY INDUSTRIES

IS networks have multiple synergies occurring between companies and industries inside the network, where the term “synergy”, here applied, refers to a single company-to-company exchange within the network, being it physical (e.g. waste or by-product) or not (e.g. knowledge and information).

Three types of industrial synergies can occur: utility sharing, joint service provision and by-product exchanges (Chertow, Ashton, & Espinosa, 2008). The first, utility sharing, consists in the joint use and management of regularly used resources for instance energy, water and waste water treatment facilities. The second, joint service provision, consists of meeting mutual interfirm needs for secondary activities, such as stationary and document services, security, among others. Finally, the third, by-product exchanges, consists in exchanges of by-products or wastes between companies to use as a replacement for commercial products or raw materials (Chertow M. , 2007).

There have always been resource exchanges between industries, even since primeval times, so there is a need to separate IS from other types of exchanges. In that sense, Chertow (2007) defined that in order for an exchange to be considered as a basic type of IS there must be, at least, three different entities involved in exchanging, at least, two different resources. Chertow called this criterion a “3-2 heuristic”. Exchanges that do yet not meet this IS criterion but have the potential to expand, such as bilateral or multilateral exchanges can be referred to as “kernel” or “precursor” (Chertow M. , 2007).

Despite the potential benefits inherent to IS it is far from being an easy concept to apply, since there can be numerous barriers to IS development. These barriers are better explained on section 2.1. of this thesis, which is followed by a selection of case studies with oil refining industries where the concept was successfully applied.

2.1. KEY ASPECTS TO INDUSTRIAL SYMBIOSIS DEVELOPMENT

Like previously stated, the process to apply the IS concept is not always a smooth one. This process may be easier or harder depending on some key aspects. In the literature these aspects are described as drivers or barriers to IS development, depending on their influence in the process. On this thesis the focus will be more on the barriers to IS development rather than the drivers due to the thesis methodology development goals. Brand & de Bruijn (1999) separated the barriers found in five categories (Brand & de Bruijn, 1999):

i. *Technical Barriers*: there is the possibility that industries present in a region do not fit together, in way that it might prove to be impossible to find a proper receiver for a waste or by-product stream within a region. Geographical distances may also be prohibitive for utility sharing synergies.

ii. *Information Barriers*: these make it difficult to find both new uses for by-products and wastes as well as alternative raw material supplies. Poor quality information or no information at all regarding demand and potential supply may hinder potential markets.

iii. *Economic Barriers*: if a reliable market for the wastes/by-products is inexistent, there is no incentive to search for inputs substitutes on those streams. Also, for the synergy to arise there needs to be a financial capacity from the companies involved to develop that process into a reality. Lastly, a cost benefit analysis may show that investments in synergy projects might not meet the payback time and profits desired by the companies, which may be due to uncertainties in the quality and reliability of the supply in the synergy (CECP, 2007).

iv. *Regulatory Barriers*: the regulatory structure/laws of a region may prevent the linking of industries or industrial processes in that region. The definition of waste in regulations proves to be a barrier, in cases where a by-product is defined by environmental regulation as waste, a potential receiver for that by-product may need to fulfill additional requirements to receive and reuse that "waste", which raises the management costs (Costa, 2011).

v. *Motivational Barriers*: all the entities involved, whether it be the industries, government or other stakeholders, must be willing to cooperate and commit themselves to the synergies development process. Companies may also not be very pleased to provide information about their production process for competition reasons hence why trust is a very important aspect.

Other authors like Heeres *et al.* (2004) suggested slightly or more detailed breakdowns of these categories of barriers but, overall, the range of barriers cited in the literature is covered by Brand & de Bruijn (1999) proposal. Harris (2004) came to the conclusion that instead of a specific barrier it was not rarely a combination of small barriers that led to the unsuccessful application of the IS concept.

2.2. INDUSTRIAL SYMBIOSIS CASE STUDIES – OIL REFINERIES

Nowadays it is possible to find several documented case studies of industrial symbiotic networks all around the world (Lowe, 1997; Harris S. , 2004; Jacobsen & Anderberg, 2004; Chertow &

Lombardi, 2005; van Beers, Corder, Bossilkov, & van Berkel, 2007; Chertow, Ashton, & Espinosa, 2008). A wide range of different companies and industries establish by-product and/or utility synergies among themselves, however, for the purpose of this thesis, the focus will be on industrial symbiotic networks that include oil refineries. The case study analysis will be focused on the waste/by-product streams in which the refineries take part. The case studies selected for analysis were: Forth Valley, United Kingdom (UK); Guayama, Puerto Rico; Kalundborg, Denmark; Kwinana Industrial Area, Australia; and Map Ta Phut Industrial Estate, Thailand.

2.2.1. Forth Valley, UK

The Forth Valley region is located in the UK, on the central belt of Scotland and comprehends the city of Edinburgh and the industrial complex of Grangemouth. The Grangemouth industrial complex consists, in its majority, of petrochemical and chemical companies. The Grangemouth Port, one of the main ports in the UK, and the Grangemouth oil refinery are two major contributors to the local economy.

In 1992 the Grangemouth Development Group (GDG) was formed. The GDG is an organization formed by the major companies at Grangemouth, the Local Enterprise Council, Forth Ports and Falkirk District Council. The main objective of the organization was to improve the competitiveness of the local industry and create more jobs. The continuing work and high level of association made the companies highly receptive to the research and to the concept of IS (Harris & Pritchard, 2004).

The first synergies to occur in the Forth Valley region were amongst the petrochemical companies, mainly the BP oil refinery and the petrochemical complex of Grangemouth. Harris (2004) found 26 existing synergies in Grangemouth (Figure 1) and the surrounding Forth Valley area (Figure 2), as well as the potential for 16 new ones to occur.

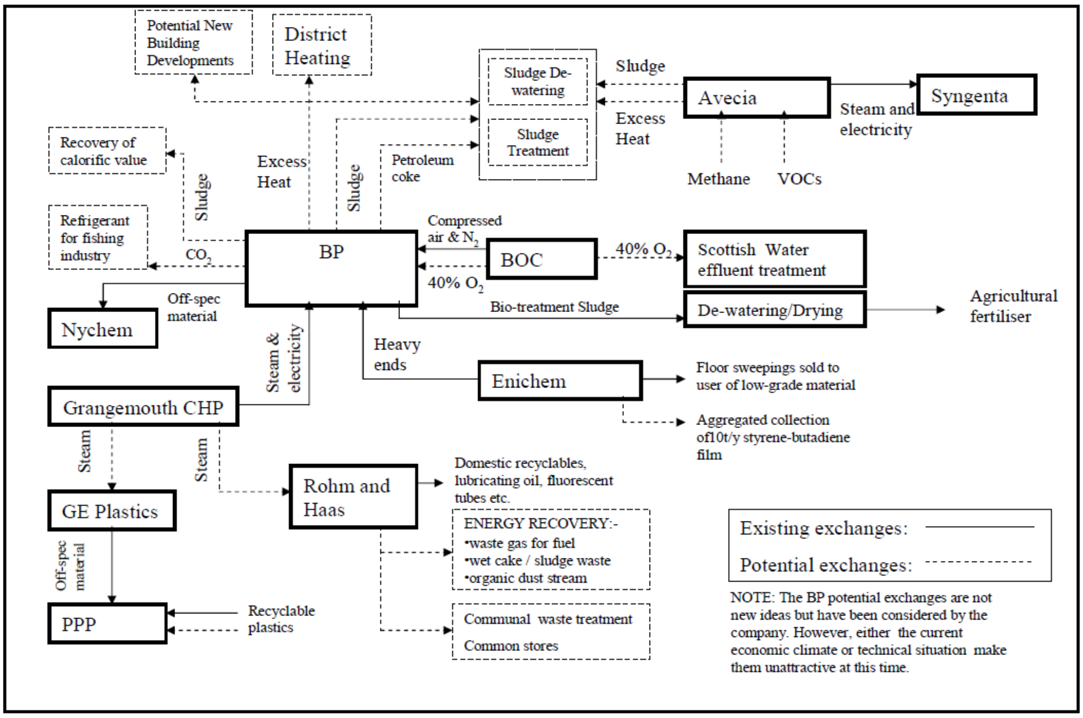

Figure 1 – Existing and potential synergies at Grangemouth. (Harris S. , 2004)

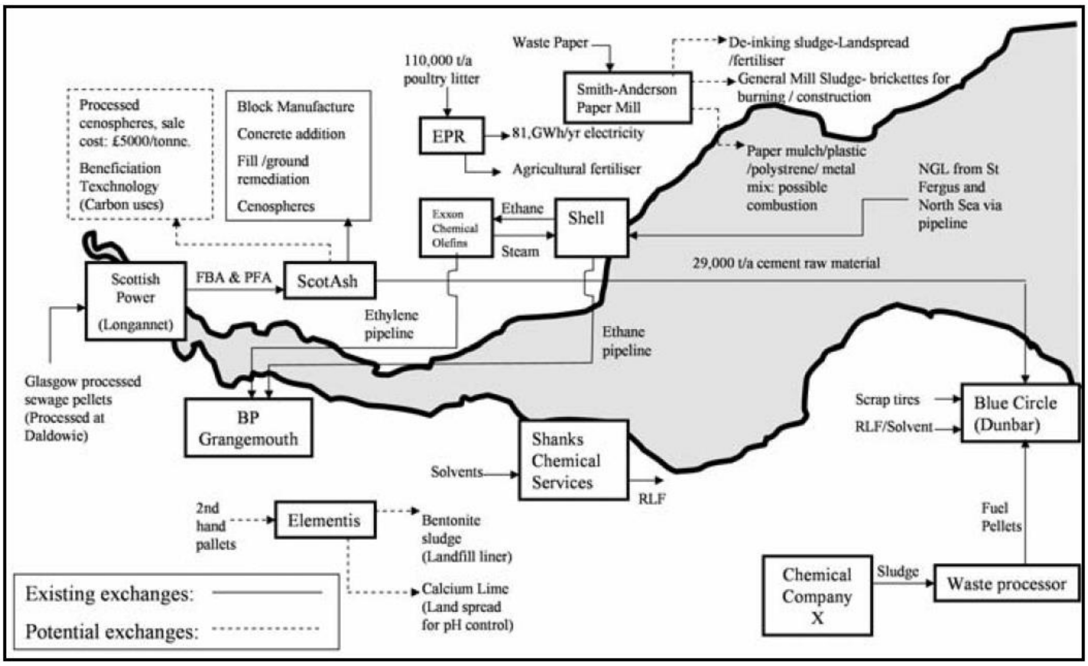

Figure 2 - Existing and potential synergies in the Forth Valley region. (Harris S. , 2004)

There were four on going examples of symbiotic activity involving the oil refinery, owned by BP. Those examples were (Harris S. , 2004):

- BP refinery was supplying off-spec material to Nychem, a plastic manufacturer;

- The bio-treated sludge from the oil refinery was de-watered and/or dried and sold as a fertilizer;
- A combined heat and power station supplied steam and electricity to the oil refinery and to a fertilizer manufacturer as well;
- And a chemicals manufacturer also supplied steam to the BP refinery.

As noted on Figure 1, the potential exchanges involving BP were not new findings and had been considered by the company, but due to the economic climate or the technical situation, at the time, they were unattractive (Harris S. , 2004).

2.2.2. Guayama, Puerto Rico

Guayama is a city and municipality located in Puerto Rico on the southern coastal valley region with a population of 45 362 (United States Census Bureau, 2013). The current industrial activity in Guayama started being developed in the mid-twentieth century after a period of light industrialization. The industrial zone of Guayama comprehends a fossil fuel power plant, an oil refinery, pharmaceutical plants and some light manufacturing businesses. The existent evolving network of inter firm exchanges in this industrial zone was analyzed by Chertow (2005). This analysis was made considering both environmental and economic benefits resulting from the synergies.

The exchanges started coming to picture in the mid-1990’s when the power plant, owned by AES, needed to find a steam host in order to fulfill Puerto Rico Electric Power Authority (PREPA or AEE by its Spanish acronym) requirement for a “qualifying facility” (QF). In order to maintain this QF status the facility has to use at least 5% of its energy output for products other than electricity, and if this QF status was not maintained, AES would not be able to sell electricity to PREPA as an independent generator (for a more detailed description of the QF requirement status see Chertow et al., 2005). Since the AES power plant was next to a refinery, owned by Chevron Philips (just Philips at the time), AES Guayama built the pipeline infrastructure necessary to provide steam to the refinery. The symbiosis occurring in Guayama are illustrated on Figure 3.

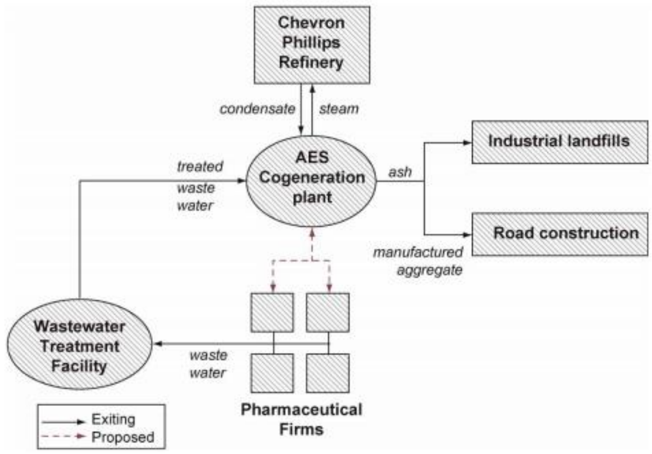

Figure 3 – Industrial symbiosis occurring in Guayama, Puerto Rico. (Chertow, Ashton, & Espinosa, 2008)

Before the steam exchange, the refinery process steam was generated by four industrial boilers burning high sulfur (2.5%) no. 6 residual fuel oil and two of those boilers were going to be replaced by steam from the power plant (Chertow & Lombardi, 2005). Since 2004 the refinery is producing a new product line with reduced process steam need, due to an extensive reengineering process that began in 2001. While all four boilers are down, if there was no steam provided by the power plant, two boilers would still be required to provide the necessary process steam to the refinery, even after the reengineering process.

The net emissions impact calculation by Chertow (2005), accounted for both the decrease in decommissioning two industrial boilers at the refinery and the corresponding increase in air emissions generated by the power plant to produce process steam for the refinery. The results showed a reduction in the emissions of SO_2, NO_x, and PM_{10}, this reduction was of 99.5%, 84.4% and 95.3% respectively. The results also showed an increase of 60.0% and 33.8% of CO and CO_2 emissions respectively, due to switching from oil to coal.

The economic impact of the steam exchange between the power plant and the refinery was estimated (to see more detailed information on the assumptions behind the estimate see Chertow et al., 2005). The refinery is estimated to have avoided costs at around $USD 11.7M and a net economic gain from the symbiotic relationship at any steam price under $9.35/k lb. steam delivered. The difference between the costs of production ($2.75/k lb. for the power plant and $9.35/k lb. for the refinery) creates an estimated $8.27M economic surplus and its distribution will depend on the price negotiated between the two companies and on the costs of producing the steam of each of company (Chertow & Lombardi, 2005).

The results show that this symbiotic relationship brings both economic and environmental benefits with the only drawback being the increase in CO and CO_2 emissions.

2.2.3. Kalundborg, Denmark

Kalundborg is one of the most renowned and documented examples of an industrial symbiotic network (Ehrenfeld & Gertler., 1997; Lowe, 1997; Chertow M. , 2000; Jacobsen & Anderberg, 2004; Jacobsen, 2006; Chertow M. , 2007). The synergies began to be established, spontaneously, in the 1970's and were driven, at least partially, by regulatory demands that made the synergies between allocated companies economically sound (Lowe, 1997). The partner enterprises involved in the Kalundborg network include a power plant, an oil refinery, a biotech and pharmaceutical company, a plasterboard producer, a company that handles waste and contaminated soil for recycling and recovery, a waste treatment company, a waste water treatment company and the Kalundborg municipality itself (Kalundborg Symbiosis, 2013). The evolution and diagram of the Kalundborg symbiosis is visible on Figure 4. The symbiosis are based either on water, solid waste or energy exchanges.

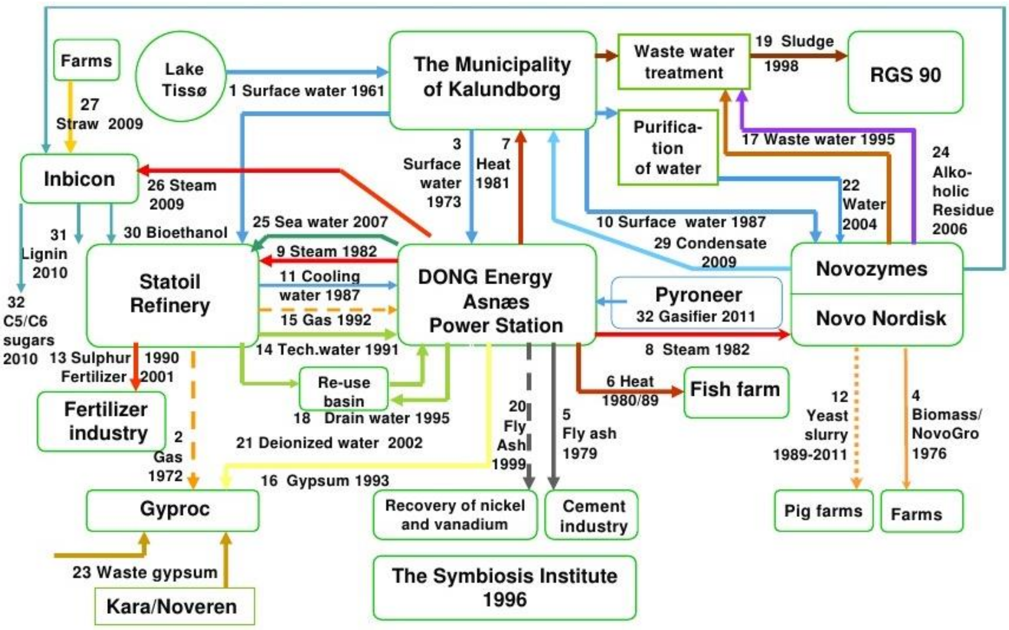

Figure 4 - Diagram of the symbiotic network in Kalundborg, Denmark. (Kalundborg Symbiosis, 2013)

The following exchanges and the results of those exchanges were described by Jacobsen (2006) and the evaluation is based on a quantitative data record spanning the period 1990-2002. In Kalundborg, the refinery supplies its waste water and cooling water to the power plant to be reused. The power plant uses the waste water for secondary purposes and the cooling water as an input for the desulfurization process, as well as feeder water for the boilers that produce steam and electricity. The refinery also receives some steam from the cogeneration power plant, the rest of the steam needed by the refinery comes from production-related in-house steam generation capacity that is partly supplied by preheated boiler water from the power plant. In the refinery, 98% of the water input is symbiotic in character and approximately 4% of the energy input, in 2002, was part of the steam-related symbiotic activities.

The cooling water delivered by the refinery to the power plant is based on water substitution and cascading. The refinery uses surface water as cooling water, which is then piped to the power plant that uses it instead of surface water. The investment required, for this cooling water exchange, for technical installations and piping was 2.0 million DKK, and it was shared by the partners at the time of project initiation. The cooling water price is linked to the price of surface water by a 50% discount. With this project the refinery gained a direct saving of approximately 1.8 million DKK or approximately US$228 000, in 2002. The refinery also gained an indirect saving due to a postponed investment of 8–10 million DKK in an extended waste water treatment facility, which would have had to treat the cooling water before discharge.

When it comes to waste water, it partly replaces the intake of surface water and cooling water by the power plant. The refinery delivered around 9 000 m^3 of waste water to the power plant, in 2002, and over 1.1 million m^3 in the 1992-2002 period. This exchange required a total investment of 2 million DKK at the time of initiation. To the refinery, since the waste water is a giveaway, the economic benefit is mainly related to the observance of discharge permissions and improved upstream availability of surface water due to a reduced intake by the power plant.

Since the refinery was capable of producing its own process-related steam an increase on the steam market price meant an increase in in-house production and a decrease in the delivery of steam to the refinery. Due to this in-house process-related production steam increase, the refinery was experiencing temporary shortages of pretreated boiler water. Piping treated boiler water from the power plant to the refinery allowed the refinery to shave its peaks and avoid an investment of 10 million DKK, that otherwise would have to be made to extend its own pretreatment facility. The investment necessary for this symbiotic project was 1.5 million DKK, the investment was relatively small because it used existing pipelines and infrastructures.

In addition of the exchanges described by Jacobsen (2006) and after an analysis of Figure 4, that represents the Kalundborg network, we can see that there are other symbiosis involving the oil refinery, such as the joint reuse of a basin for waste water from the power plant and oil the refinery and a supply of sulphur from the oil refinery to the fertilizer industry.

Until 2004, the total investment for the involved industries in the Kalundborg symbiosis activities had been US$75 million with the yearly economic profit adding up to US$15 million and with each single project having, on average, a five year payoff time. The main reason for this economic profit is the effect of resource savings (Jacobsen & Anderberg, 2004).

2.2.4. Kwinana Industrial Area, Australia

Kwinana Industrial Area was established in the 1950's and is spread along 8 km of coastal land on the south of Perth, Western Australia. The area was established to accommodate the development of major resource processing and other heavy industries in Western Australia (van Beers, 2009). The synergies that occur in the Kwinana Industrial Area are well documented in the literature, both by-product synergies as well as utility synergies (Sinclair Knight Merz, 2002; van Berkel, van Beers, & Bossilkov, 2006; van Beers, Corder, Bossilkov, & van Berkel, 2007; van Beers, 2008; van Beers, 2009). By 2008, the number of synergies occurring in the Kwinana Industrial Area was 47, with 32 of these being by-product synergies (Figure 5) and the remaining 15 being utility synergies (Figure 6) (van Beers, 2008).

The industries present in the Kwinana Industrial Area, include an alumina refinery, a nickel refinery, a titanium dioxide pigment plant, lime and cement kilns, an oil refinery and a pig iron plant, which are complemented by a variety of chemical producers (Sinclair Knight Merz, 2002). There are important utility operations, which include two power stations, two cogeneration plants, two air separation plants, a grain handling and export terminal, port facilities and water and waste water treatment plants (van Beers *et al.*, 2007).

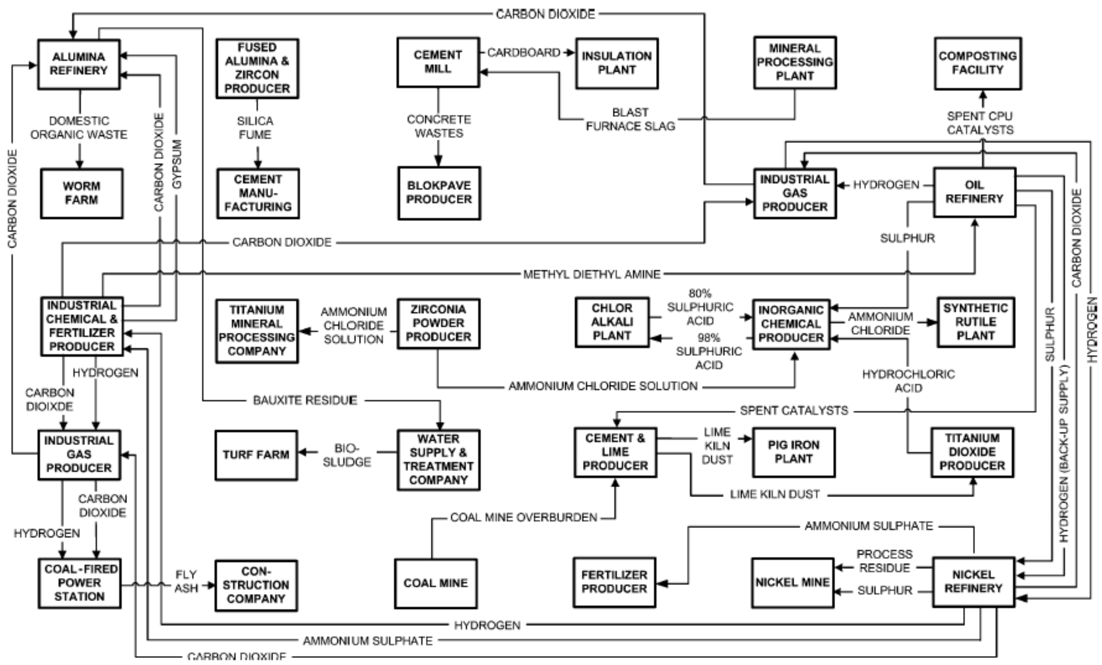

Figure 5 – By-product synergies occurring in the Kwinana Industrial Area, Australia. (van Beers, Corder, Bossilkov, & van Berkel, 2007)

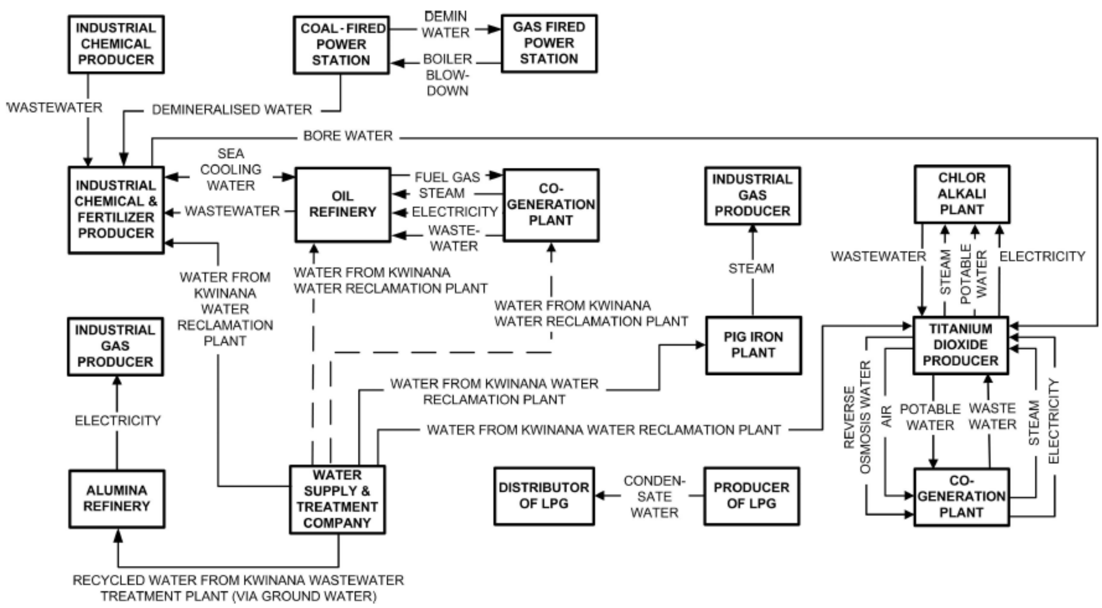

Figure 6 – Utility synergies occurring in the Kwinana Industrial Area, Australia. (van Beers, Corder, Bossilkov, & van Berkel, 2007)

The oil refinery, owned by BP, was one of the first industries in Kwinana and started production in 1954. As of 2008, the BP refinery was involved in 6 by-product synergies and 3 utility synergies plus another one that was planned and being finalized. The identification and summary of all the by-product and utility synergies in the Kwinana Industrial Area was made by van Beers (2008).

In one of the by-product synergies, the oil refinery gives its excess hydrogen to an industrial gas producer and supplier (BOC Gases) that then, after the necessary treatment, provides the hydrogen for CUTE (Clean Urban Transport for Europe) Bus Project and others. The refinery also provides hydrogen for the nickel refinery as a back-up supply. In another by-product synergy, the phosphorous content of spent CPU catalysts in the refinery is leached out at Oackford Organics and is used as compost addition. The elemental sulphur, that is a by-product in the oil refinery, is received by the nickel refinery and a chemical producer (Coogee Chemicals). The BP refinery is also involved in a by-product synergy with Cockburn Cement for the recycling of spent RCU catalysts in cement manufacturing process. The oil refinery is also a receiver in the synergies at Kwinana, it receives MDEA (methyl diethyl amine) from a chemical and fertilizers manufacturer and supplier (CSBP).

When it comes to utility synergies, the waste water output from the oil refinery is an input to CSBP wetland cells. The CSBP and the BP refinery also exchange sea cooling water between themselves. Another utility synergy involves the BP refinery and the Kwinana Cogeneration Plant, which provides steam, electricity and waste water to the refinery. The other planned utility synergy is part of the Kwinana Water Reclamation Project, where the BP refinery would receive high grade industrial processing water from Woodman Point Waste water Treatment Plant and would later dispose the industrial water via Sepia Depression Ocean Outlet Landline (SDOOL).

The Kwinana Industrial Area is the state largest industrial area and is a major source of revenue for the State and Australian economies with an annual output worth A$8.7 Billion (Sinclair Knight Merz, 2002). In Kwinana, are still being identified, assessed and implemented other regional synergy opportunities by a step-by-step methodology (van Beers, 2008).

2.2.5. Map Ta Phut, Thailand

The Map Ta Phut Industrial Estate, which is managed by the Industrial Estate Authority of Thailand (IEAT), was established in 1985. Map Ta Phut is located on the eastern seaboard of Thailand near the city of Rayong and is one of the biggest industrial estates in the country due to deliberate government policy aimed at encouraging the economic development in that region (Pinyochatchinda & Walsh, 2012). The Map Ta Phut Industrial Estate was designed for petrochemical industries and its downstream processes due to the discovery and extraction of hydrocarbons in the Gulf of Thailand.

The IEAT together with GTZ (German Technological Collaboration Agency) implemented a project for the development of eco-industrial estates and networks of which the main objective was “to enable industrial developers, operators and enterprises, in selected industrial estates, to apply the Eco-Industrial Development approach to develop their businesses (GTZ)". Map Ta Phut was one of the industrial estates selected for the project.

Map Ta Phut is Thailand's largest industrial port and the industrial estate covers an area of 1 447 ha, comprising 89 facilities and employing about 11 685 people (GTZ/IEAT, 2001 *in* Centre of Excellence in Cleaner Production, 2007). The main industries present in the estate are oil refining, chemical and fertilizer, petrochemical, and steel industry. The identification and development of the regional resource synergies is managed by the local IEAT with the purpose of rationalize resource utilization, reduce waste and emission generation, enhance quality of life for the local community, and bolster competitiveness (Homchean, 2004 *in* CECP, 2007).

A total of seventeen regional synergies appear to be active in the Map Ta Phut industrial estate, from which at least 2 include the oil refineries. One of them consists in the supply of naphtha and condensate by-product from the oil refineries to be used in the process production of white spirit solvent, diesel, fuel oil and on the other synergy the liquid sulphur, by-product from the oil refineries, is used for fertilizer production (GTZ/IEAT, 2001; Homchean, 2004 *in* CECP, 2007).

2.2.6. Case studies synthesis

Table 1 summarizes all the exchanges, in which the oil refineries are involved, occurring in the case studies analyzed.

Table 1 - Summary of symbiosis analyzed on the case studies

Region	Synergy Description	Source
Forth Valley, UK	Oil refinery supplies off-spec material to plastic manufacturer	(Harris S. , 2004)
	Bio-treated sludge from oil refinery de-watered and/or dried and sold as fertilizer	(Harris S. , 2004)
	Combined heat and power station supplies steam and electricity to oil refinery and fertilizer manufacturer	(Harris S. , 2004)
	Chemicals manufacturer supplies steam to oil refinery	(Harris S. , 2004)
Guayama, Puerto Rico	Power plant supplies steam to the refinery	(Chertow & Lombardi, 2005)
Kalundborg , Denmark	Excess gas from the refinery to power plant and plasterboard manufacturer	(Jacobsen, 2006)
	Power plant supplies steam to oil refinery	(Jacobsen, 2006)

	Cooling water and waste water from oil refinery is supplied to the power station	(Jacobsen, 2006)
	Sulphur from oil refinery to fertilize industry	(Kalundborg Symbiosis, 2013)
	Reuse basin for waste water from power plant and oil refinery	(Kalundborg Symbiosis, 2013)
Kwinana Industrial Area, Australia	Alcoa alumina receives spent-catalyst from oil refinery to mix it with red mud to neutralize the pH in rehabilitation site	(van Beers, 2008)
	Oil refinery supplies spent residual cracker unit catalyst to Cockburn Cement for using it in cement production	(van Beers, 2008)
	Oil refinery supplies by-product sulphur to the nickel refinery and a chemical producer	(van Beers, 2008)
	Oil refinery receives MDEA from CSBP	(van Beers, 2008)
	CSBP and the oil refinery exchange sea cooling water between themselves and waste water output from the oil refinery is an input to CSBP wetland cells	(van Beers, 2008)
	Kwinana Cogeneration plant / oil refinery cogeneration project including exchange of fuel gas, steam, electricity and waste water	(van Beers, 2008)
	Water Corporation supplies high-grade treated effluent from KWRP to the oil refinery for high quality process water	(van Beers, 2008)
	Oil refinery and industrial gas producer supply hydrogen for the CUTE hydrogen trial	(van Beers, 2008)
Map Ta Phut, Thailand	Liquid sulphur from oil refinery to fertilize industry	(GTZ/IEAT, 2001; Homchean, 2004)
	Naphtha and condensate derived as by products which are used in the production process of aromatics	(GTZ/IEAT, 2001; Homchean, 2004)

From the case studies analyzed is it possible to note that there is IS potential in the oil refining sector. In the case studies, the symbiosis taking place were mainly involving one material resource exchange and other water, energy and industrial gases exchanges like is depicted on Table 2.

Table 2 - Main exchanges in the case studies reviewed

		Case Studies
Material resource	By-product sulphur	Kalundborg, Kwinana & Map Ta Phut
Water, energy and other industrial gases	Electricity	Forth Valley, Kwinana & Map Ta Phut
	Steam	Forth Valley, Guayama, Kalundborg, Kwinana & Map Ta Phut
	Naphtha	Forth Valley, Kwinana & Map Ta Phut
	Other industrial gases	Kalundborg & Kwinana
	Water	Kalundborg & Kwinana

The potential of the Sines refinery for the exchanges found in the case studies will be further evaluated on section 5.1. of this thesis.

CHAPTER 3: METHODOLOGY

The methodology goal is to find and evaluate potential new synergies. The methodology applied for the evaluation of the possible kernels is illustrated on Figure 7 and consists in four separate stages: Pre-screening (3.1); Screening (3.2); Life cycle analysis (3.3); and Financial analysis (3.4). The first stage, pre-screening, is where the potential new exchanges are unveiled. The screening stage was developed considering the barriers to IS development and the main goal in this stage is to be able to swiftly find potential exchanges that face barriers to its development. Only potential exchanges that successfully pass this screening stage will be subject to evaluation. The evaluation will be made in two separate stages, a life cycle analysis which will be used as an environmental evaluation and the other stage will be a financial analysis to evaluate the economic viability of the exchange. A more detailed description of each stage can be found ahead.

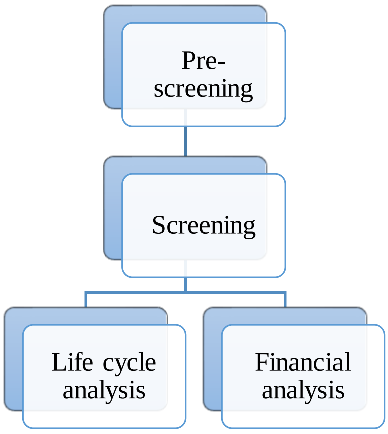

Figure 7 - Methodology scheme

3.1. PRE-SCREENING

The pre-screening methodology goal is to discover potential new exchanges. This objective is achieved by analyzing similar case studies that are documented in the literature. The exchanges found in the case studies are then considered and evaluated for the case study where the methodology is being applied.

3.2. SCREENING

The screening methodology was created based on a literature review of the main barriers for IS development. The methodology includes regulatory, economic, environmental and social aspects. The screening methodology for each possible kernel consists on the evaluation of nine different categories: Regulatory context; Geographic proximity; Technical viability; Capital availability; Payback period; Virgin resource use avoided; Waste re-use/recycling promoted; Firms willingness to cooperate; and Overall perception of risks. The parameters were evaluated on a scale from 1 to 5, with 1 being not favorable and 5 being highly favorable. In order for the kernel being evaluated to pass on to the life cycle and financial analysis stages it needs to have, at least, an overall score of 27 from the possible 45. However, if one of the parameters is evaluated as ‘not favorable’ (1) the synergy will not pass the screening stage, the only exception concerns the parameter ‘Waste re-use/recycling promoted’ which may not be applicable. Figure 8 illustrates the screening evaluation.

Regulatory context

1	2	3	4	5
Not favorable				Highly Favorable

Geographic proximity

1	2	3	4	5
Not favorable				Highly Favorable

Technical viability

1	2	3	4	5
Not favorable				Highly Favorable

Capital availability

1	2	3	4	5
Not favorable				Highly Favorable

Payback period

1	2	3	4	5
Not favorable				Highly Favorable

Virgin resource use avoided

1	2	3	4	5
Not favorable				Highly Favorable

Waste re-use/recycling promoted

1	2	3	4	5
Not favorable				Highly Favorable

Firms willingness to cooperate

1	2	3	4	5
Not favorable				Highly Favorable

Overall perception of risks

1	2	3	4	5
Not favorable				Highly Favorable

Figure 8 - Screening evaluation.

3.1.1. Regulatory context

The most influential factors in context setting are, perhaps, policies and policy instruments such as regulation (Costa, 2011). In some reported cases in the literature, policies and regulation have had a negative effect in the establishment of IS networks, acting as barriers, rather than a positive one, acting as drivers (Desrochers, 2000; Desrochers, 2004).

3.2.2. Geographic proximity

The distance between firms and industries is a known very important factor for the establishment and development of symbiotic networks. Chertow's (2000) definition of IS itself states that one of the key characteristics for the emergence of IS are "*the synergistic possibilities offered by geographic proximity"*. Despite being a key characteristic it is somehow difficult to quantify this proximity. In this sense, Jensen and colleagues (2011) attempted to quantify 'geographic proximity' in the IS context based on the analysis of synergies that occur during the first five years of operation of the NISP (National Industrial Symbiosis Programme). Their findings were that, within the UK, the 'geographic proximity' corresponded to 20.4 miles (approximately 32.8 km), however they also found that it may differ depending on the resource being exchanged ranging to a maximum of 269.2 miles (approximately 433.2 km).

3.2.3. Technical viability

The technical viability of a possible symbiosis is a major factor to take in consideration. Difficulties to the implementation of a successful IS may arise due to a possible lack of technological capacity of companies to integrate wastes/by-products as raw materials or due to inadequate quality and quantity of the resource flows.

3.2.4. Capital availability and payback period – Economic parameters

The main goal of an industry is to generate profits (to create value for shareholders) and for that reason the economic aspects are, usually, one of the main drivers for companies to consider IS. Even when considering symbiosis that are economically viable, some companies may still find them unattractive if the payback period is too high or other financial indicators (e.g. IRR, NPV) are not aligned with their goals. Another possible scenario to reject a symbiosis is one in which a company does not have the financial capacity to invest to make the symbiosis a reality, even in cases where the symbiosis is economically viable.

3.2.5. Virgin resource use avoided and waste re-use/recycling promoted – Environmental parameters

There are documented cases of better environmental performance by the companies when taking part in symbiotic networks (Chertow & Lombardi, 2005; Jacobsen, 2006). The promotion of the re-utilization/recycling of wastes and the reduction of the intake of virgin resources by companies is in line with a more sustainable economy and sustainable development.

3.2.6. Firms willingness to cooperate

Cooperation is vital when thinking of IS, when engaging in IS the companies must already be willing to cooperate and establish links amongst themselves. Since this cooperation in light of IS implies sharing some knowledge, like a process inputs and outputs, trust and confidentiality issues may rise. Since trust plays an important role in this cooperation it is said that IS emerges more easily when the companies involved already have some type of connection amongst themselves, either a business relationship or a good social relationship between company managers.

3.2.7. Overall perception of risks

A symbiosis is subject to many risks. One of the risks is the reliability of the supply of the material being exchanged with another company, this reliability may be affected in cases where the production of the supplier decreases or ceases due to the economic setting or other (Lowe, 1997). Another risk is the long term viability, in IS projects where a larger investment may be necessary, the companies need to be sure that it will last, at the very least, for the payback period of the investment made. A risk to take in consideration as well is the regulatory risk, legislation suffers alterations from time to time so there is an inherent risk of a symbiosis being negatively affected by one of those alterations. Another risk that every company is already subjected to, even without have any symbiotic activity, is risks related to climate change.

3.3. LIFE CYCLE ANALYSIS

The life cycle analysis will be made as an environmental evaluation, to evaluate the new potential synergies environmental performance.

Life cycle assessment (LCA) was developed around 1970 (Klöpffer, 1997) and can be used as an indicator that, along with others, may help quantifying sustainable development (Rebitzer, et al., 2004). LCA and can be described as a methodological framework to assess the environmental impact of a product from '*cradle to grave*'. This methodological framework, illustrated on Figure

9, consists of four phases: goal and scope definition; life cycle inventory (LCI); life cycle impact assessment (LCIA); and interpretation (International Standard ISO 14040, 1997).

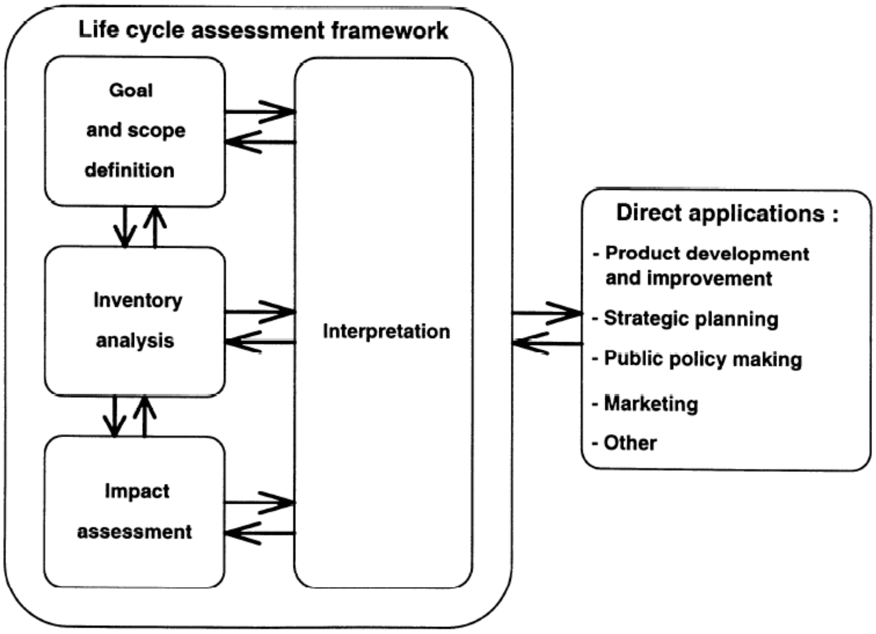

Figure 9 - Methodological framework for LCA. (International Standard ISO 14040, 1997)

On the first phase, goal and scope definition, the goal of the LCA study should be well defined and shall be in line with the application intended and the scope of the study should be made considering all relevant items (International Standard ISO 14041, 1998). The goal and scope of the study should fulfil the requirements of ISO 14040:1997. The following phase, life cycle inventory analysis, is where the data collection and calculation procedures take place and the results obtained in this phase should be interpreted according to the goal and scope of the study (International Standard ISO 14041, 1998). The third phase, life cycle impact assessment, is made to examine the product system from an environmental point of view using impact categories and category indicators that are linked with the life cycle inventory results (International Standard ISO 14042, 2000). Finally, the life cycle interpretation phase, aims to analyze the results, get to conclusions, explain limitations and provide recommendations based on the results obtain on the previous phases and to provide the findings of this stage in a clear manner (International Standard ISO 14043, 2000).

To aid in LCA quite some software programs were created, SimaPro is the most widely used. The software allows you to choose between different methodologies, the Eco-indicator 99 method, for example, uses a damage-oriented approach. The emissions and resource extractions are traditionally expressed in 10 or more impact categories such as acidification, global warming, resource extraction and ecological toxicity. Instead of that, the Eco-indicator 99 method weights the different types of damage cause by the impact categories. The method considers three damage categories (PRé Consultants, 2008): Damage to Human health; Damage to Ecosystem quality; And damage to Resources. The first is expressed as the number of year life lost and the number of years lived disabled. The second is expressed as the loss of species over a certain area, during a certain period. And the last is expressed as the surplus energy needed for future extractions of minerals and fossil fuels (PRé Consultants, 2008).

Boons et al. (2011) refer LCA as a useful tool to quantify the environmental performance of an exchange or exchanges that take place in a symbiotic network. So far, LCA has been applied in very few IS studies. Mattila et al. (2012) suggest an implementation of more decision-oriented LCA methods to ensure that IS development does not result in unexpected indirect effects through market mechanisms.

After the screening stage of the methodology, this LCA methodology will be applied to the potential synergies to evaluate its environmental impacts. The LCA will be made by comparison between a situation where the IS exchanges take place and the current situation. The different flows will be analyzed.

Unfortunately, due to license and demonstration version restrictions the software that will be used for the LCA will not be SimaPro, ECO-it will be used instead. ECO-it was developed by the same company that created SimaPro and can be viewed as a simplified version of it, it contains ove 500 ReCiPe environmental impact and carbon footprint scores.

3.4. FINANCIAL ANALYSIS

The financial analysis will be made in order to evaluate the economic potential of the synergies, to assess its economic viability.

In a financial analysis, the main objective is to *"use the project cash flows forecasts to calculate suitable net return indicators"* (European Comission, 2008). The financial analysis is part of a detailed cost-benefit analysis incorporating the both the private and social perspectives. In this case only a simplified financial analysis in the private (oil refinery) perspective will be performed due to data availability constraints. The determination of the project cash flows will be computed as the differences in the costs and benefits between the scenario with the proposed synergy and a scenario without the project, being consistent with the approach adopted in the LCA. The financial analysis will account for the total investment costs and the total operating costs and revenues. The analysis will be conducted for a 10 year time horizon according to the recommendations by the EC for the evaluation of industrial projects submitted to European funds in the period 2007-2013

(European Comission, 2008). There are multiple economic indicators that could be used, however, for the purpose of this thesis the economic indicators that are going to be used are the payback period, in cases where investment is necessary, and the benefit-cost ratio in cases where there is no investment.

CHAPTER 4: CASE STUDY DESCRIPTION – GALP OIL REFINERY

The case study where the methodology developed is going to be applied is an oil refinery owned by Galp. The refinery is situated in an industrial area in Portugal, in the municipality of Sines. Sines is located in the southwest coast of Portugal and is the location of one of the largest maritime-industrial complexes in Portugal, whose tenants include a thermoelectric power plant (owned by Energias de Portugal), the oil refinery and a polymer refinery (owned by Repsol). The complex has a large maritime port and three industrial areas: ZILS 1 (heavy industries), ZILS 2 (lighter industries) and ZAL (logistics area of the port authorities). Figure 10 shows an aerial view of the complex where the oil refinery is located.

Figure 10 - Aerial view of the maritime-industrial complex of Sines. (AICEP, 2013)

The refinery started operating in 1978 and was part of some major political, economic and social changes that occurred in Portugal in the 1970's and 1980's that led to the start of some big projects. The construction of the refinery was part of an export strategy to the United States of America (USA), at a time of international expansion of petroleum products consumption, and is strategically located in a deep water port on the busiest oil tanker route in the world (Galp Energia, 2013).

This strategic industrial unit is vital to Portugal's economic activity and covers has an area of 320 ha, with a storage capacity of 3 million m^3, of which 1.5 million m^3 is crude oil and the remaining final and intermediate products and intermediate products such as gas, gasoline and diesel (Galp Energia, 2013). Figure 11 shows an aerial view of the refinery.

Figure 11 - Aerial view of Sines refinery. (Galp Energia, 2013)

The Sines refinery is one of the largest in Europe with a distilling capacity of 10.9 million tons per year, or 220 000 barrels a day, it produces gasoline, diesel, liquefied petroleum gas (LPG), fuel oil, naphtha, jet fuel, bitumen and sulphur but its processing configuration is oriented towards increased gasoline production (through its Fluid Catalytic Cracking (FCC) unit) and more recently (after a conversion project) , as of January 2013, towards maximizing diesel production through its hydrocracker unit (Galp Energia, 2013).

In terms of environmental impacts, the refinery performance can be divided into four groups: resource consumption; atmospheric emissions; liquids effluents; and waste. In terms of resource consumption, the impacts are related with water and energy consumption besides raw materials consumption like crude oil and natural gas for hydrogen production. Atmospheric emissions are mainly related to sulphur and nitrogen oxides as well as carbon dioxide and particles. The liquid effluents produced in the refinery are pre-treated before going to a waste water treatment plant. Lastly, the refinery generates industrial waste, waste comparable to urban waste and waste that is sent for recycling.

It may be important to say that the refinery recently joined the 100R project which is a voluntary environmental certification program. The main driver for the refinery to obtain this certification is to demonstrate that it adopts environmental responsible behaviors.

CHAPTER 5: APPLICATION TO THE GALP OIL REFINERY

During her PhD thesis, Costa (2011) developed a IS facilitation tool, called DISC (Database for Industrial Symbiosis Case studies) and tested it on the Sines industrial area. In a short description, this tool is a database containing categorized information describing each synergy established under an IS framework (Costa, 2011). The results of the application of the DISC tool are presented on Figure 12 and Figure 13.

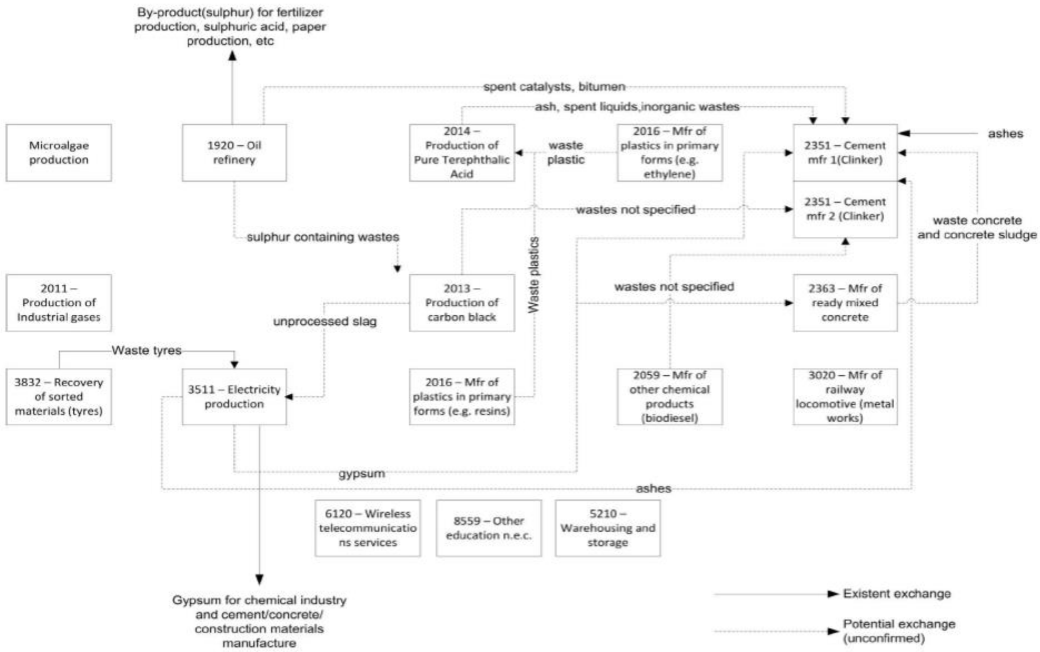

Figure 12 - Material resource exchanges at Sines industrial area. (Costa, 2011)

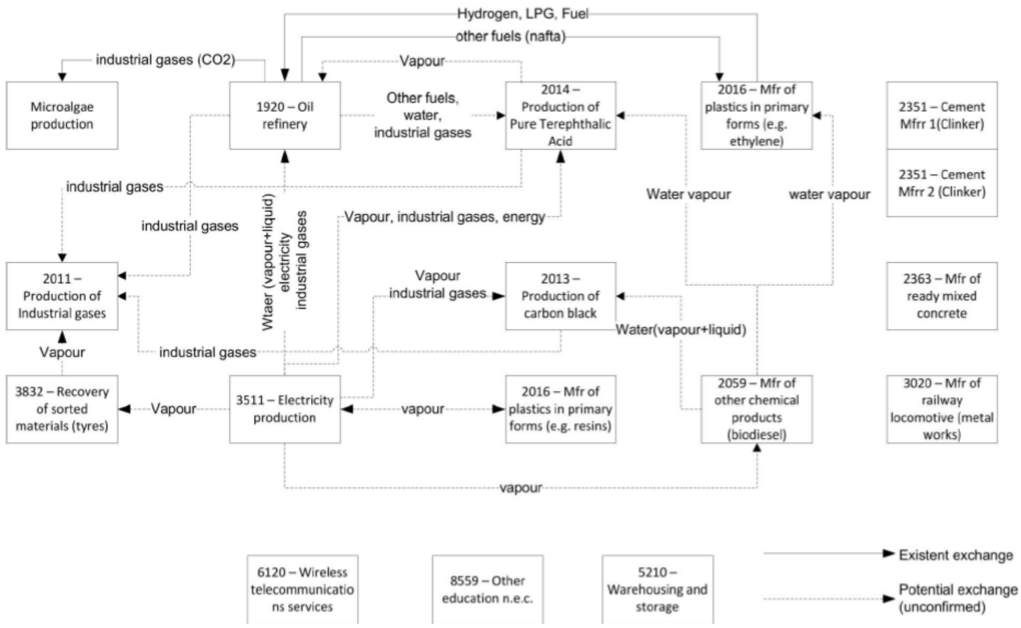

Figure 13 - Water, energy and other industrial gases exchanges at Sines industrial area. (Costa, 2011)

From these results and after a meeting with Galp refinery management, it was clarified that the oil refinery already exchanges naphtha and other industrial gases with co-located companies in the ZILS area. The refinery also used to exchange bitumen for road construction but due to the economic context of Portugal all the ongoing major highway constructions came to a halt and the refinery ceased bitumen production. In the ZILS area a microalgae production project was also considered but did not prove to be attractive enough and was abandoned (Dias, 2013).

5.1 PRE-SCREENING

From the case studies analyzed the symbiosis taking place were mainly involving one material resource exchange and other water, energy and industrial gases exchanges. Those exchanges will be now discussed regarding their potential for the Sines refinery.

5.1.1. Electricity & Steam exchanges

The Sines oil refinery made an investment of approximately €73 million on their natural gas cogeneration plant that produces steam and electrical power for the refinery. The plant, that started operating in 2009, produces 18mton of steam per year and 668GWh/year of electric energy (Galp Energia, 2013). The excess energy that is not used by the refinery is exported to the electric network. Due to this fairly recent investment the refinery is unlikely to be interested in investing in another steam or electricity project.

5.1.2. Naphtha

The refinery is already involved in an exchange concerning naphtha. The naphtha is supplied by the refinery to Repsol, a nearby plastics manufacturer.

5.1.3. Other industrial gases

In what regards other industrial gases the refinery already provides hydrogen to Repsol as well as to ArtLant, a co-located producer of purified terephthalic acid (PTA).

5.1.4. Sulphur

In the cases studies reviewed the by-product sulphur was supplied to the fertilizer industry (Kalundborg & Map Ta Phut), to a nickel refinery and a chemical producer (Kwinana). The Sines refinery already occasionally sells part of their sulphur, however, a large quantity of their sulphur is accumulating in the refinery facilities. A sulphur exchange may be considered "business as usual", however, since the refinery specifically stated to have interest in this exchange it will be further evaluated on section 5.2.

5.1.5. Water

Water exchanges were found on two of the case studies analyzed – Kalundborg and Kwinana. In Kalundborg, the oil refinery was supplying its cooling water and its waste water to the power plant and both the industries had a reuse basin for waste water. In Kwinana, the oil refinery was exchanging sea cooling water and waste water and was being supplied with high-grade treated effluent. A cooling water exchange by the refinery is further evaluated on 5.2.

5.2. METHODOLOGY APPLICATION TO CONSIDERED EXCHANGES

The potential exchanges that were considered for analysis were a sulphur exchange and water exchange. These exchanges will start by being evaluated using the screening methodology and if this screening evaluation is positive, then a life cycle assessment and financial analysis will follow.

5.2.1. Sulphur

In the case of a sulphur exchange considering the case studies and the DISC tool application, the possible applications for the sulphur would be sulphuric acid production, fertilizer production, paper production and/or to be used at a nickel refinery.

A nickel refinery cannot be a destination for the sulphur since there is none operating in Portugal. After contacting the biggest paper production company in Portugal, it was noted that they do not use elemental sulphur in their production process. The fertilizer companies in Portugal are mainly involved in the commercialization of fertilizers instead of production, however, there is some fertilizer production in Portugal. After contacting the fertilizer market leader company that produces their own fertilizers and despite being noted that they also do not use elemental sulphur in their production process some interest was shown in, at least, consider the possibility of using the elemental sulphur of the refinery, however an explicit answer was not given before the time of the conclusion of this thesis. Also, after contacting several chemical companies and a chemical companies association, we concluded that there is no sulphuric acid production in Portugal, all sulphuric acid is imported. Given the impossibility of considering an exchange with an existing industry in Portugal, a scenario where a sulphuric acid production facility would move to a location close to the refinery was considered for the analysis.

5.2.1.1. Screening

The screening methodology is now going to be applied to the case of a sulphur exchange.

Regulatory context

		3		

Not favorable — Highly Favorable

There is no legislation stopping this exchange from taking place. After the refining process on the refinery, the by-product sulphur ends up in the granulated form hence not needing any special treatment.

Geographic proximity

				5

Not favorable — Highly Favorable

The geographic distance between the supplier and receiver should be around 30km like it was described in the methodology. Considering that the receiving company would move to a location close to the refinery, the geographic proximity should pose no inconvenient.

Technical viability

		3		

Not favorable — Highly Favorable

This exchange should be technically viable because, like it was explained in the regulatory context parameter, the form in which the sulphur is presented requires no special treatment.

Capital availability

				5

Not favorable — Highly Favorable

This exchange does not require any investments by the refinery, the sulphur would only need to be transported to the receiver company. This transport could also be supported by the receiver.

Payback period

				5

Not favorable Highly Favorable

Like it was stated on the previous parameter, since the investment necessary for this exchange to take place is virtually none, the payback period does not present itself as a drawback.

Virgin resource use avoided

				5

Not favorable Highly Favorable

If the receiving company uses the sulphur being exchanged as a substitute of virgin sulphur there is a strong potential virgin resource use avoided.

Waste re-use/recycling promoted

				5

Not favorable Highly Favorable

The utilization of the by-product sulphur from the oil refinery represents a re-use of that product that would otherwise be simply deposited as waste in the refinery.

Firms willingness to cooperate

			4	

Not favorable Highly Favorable

The oil refinery is extremely willing to cooperate to make this exchange a reality.

Overall perception of risks

			4	

Not favorable Highly Favorable

The overall risks in this sulphur exchange case are relatively low. The receiving company would have a reliable sulphur source, due to the economic importance of the refinery in the national and even Iberian context it is not going to cease its activity anytime soon.

The overall result of the screening evaluation of a sulphur exchange is a score of 39 like is shown on Table 3. With this result being higher than 27 the exchange is considered promising and will be subject to a life cycle assessment and a financial analysis.

Table 3 - Sulphur exchange screening results.

Parameters	**Score**
Regulatory context	3
Geographic proximity	5
Technical viability	3
Capital availability	5
Payback period	5
Virgin resource use avoided	5
Waste re-use/recycling promoted	5
Firms willingness to cooperate	4
Overall perception of risks	4
Total	**39**

5.2.1.2. Life cycle analysis

Considering the flows of a scenario without the exchange taking place (Figure 14) and a scenario where the exchange occurs (Figure 15) an LCA could be made, however, the scenario with the exchange is the most practiced nowadays with most of the sulphur in the market being recovered sulphur from petroleum and gas sources. The method without the exchange became less common since the late 20th century (The Sulphur Institute, 2013). For this reason the LCA will not be made comparing these two sulphur origins, but instead will be made for different scenarios of transport of sulphuric acid between it being imported and it being distributed from the new potential sulphuric acid production facility close to the refinery.

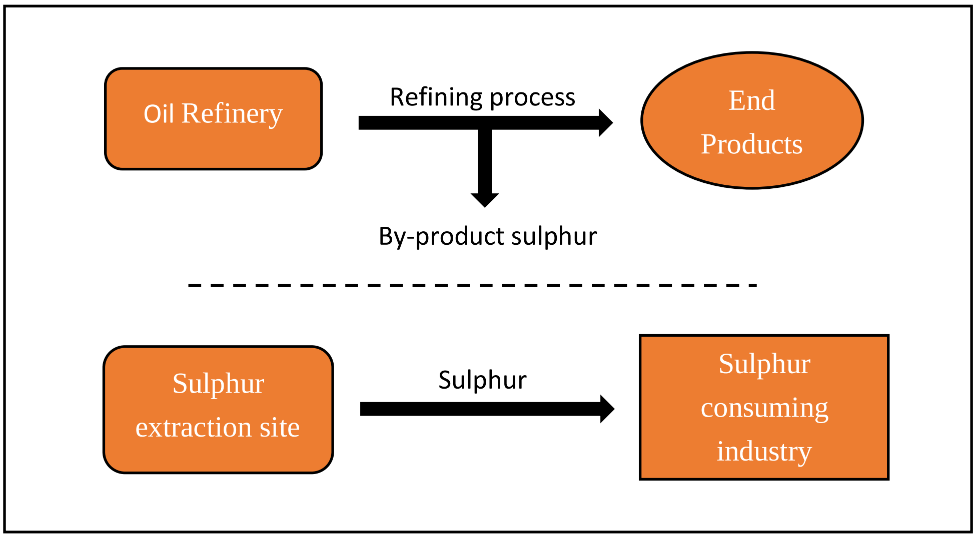

Figure 14 - Resource flows of scenario without the exchange.

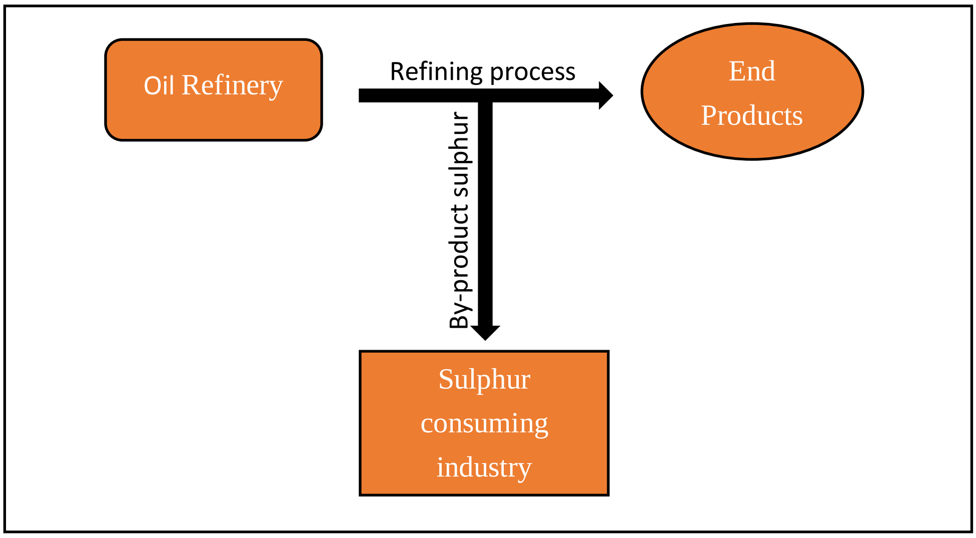

Figure 15 - Resource flows of scenario with the exchange taking place.

Due to the fact explained above, the LCA will instead be made comparing different types of transport for the sulphur acid by water in case of it being imported from China[1] or by road from a potential new production facility located near the refinery. The distance by sea from China to Portugal used will be of approximately 17341 km, based on a route from the Shanghai Terminal to the Sines Terminal (Sea Rates, 2013) and the distance by road considered will be of 500 km -

[1] Due to difficulties in getting information about the source of the sulphuric acid from Portuguese distributor companies, the source location, even though the author recognizes that it is not the most desirable, is based on a global trade website, where China is the country with the most sulphuric acid suppliers. The results can be viewed in the following link http://portuguese.alibaba.com/product-list/%25C3%25A1cido_sulf%25C3%25BArico_98%2525/--sulfuric%2Bacid%2B98%2525------1.html

because a radius of 500 km from the Sines area practically covers the entire continental Portugal. The amount of sulphuric acid transported considered will be of 4 128 ton/year, amount of sulphuric acid produced from 1 350 ton of sulphur (the explanation for this quantity can be seen on section 5.2.1.3) and the carbon footprint resulting from this LCA accounts for the CO_2 emissions in one year alone. The functional unit was 1 ton of sulphuric acid. In the case of the transport from China by sea the reference flow was equal to 4 128 ton multiplied by 17 341 km. And in the case of the transport from Sines by road it was equal to 4128 ton multiplied by 500 km. The results obtained are shown on Figure 16 and will be further discussed on section 5.3.

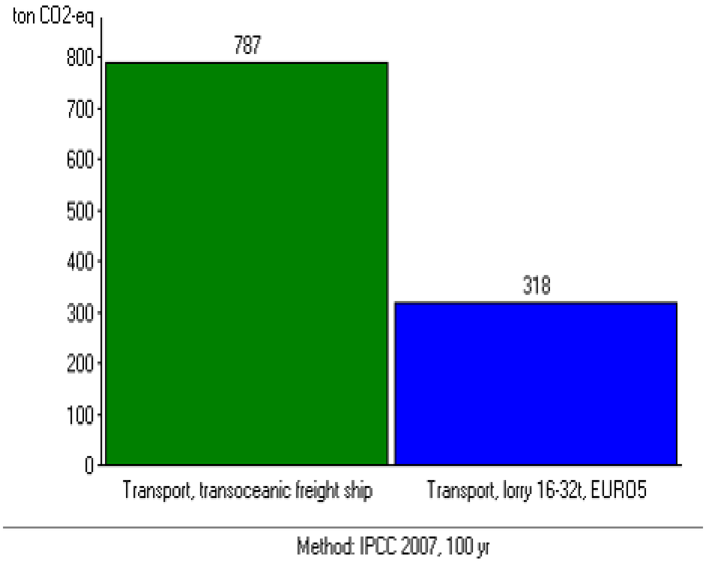

Figure 16 – Sulphuric acid transport LCA results.

5.2.1.3. Financial analysis

The financial analysis is going to be made from the oil refinery perspective and the following aspects were considered:

- The by-product sulphur from the refinery has the same quality as market sulphur;
- The quantity introduced in the market by the refinery is not enough to affect market prices;
- The discount rate considered will be equal to 0;
- Income is represented by the revenue from the sulphur sales and the avoided storage costs;

- The expenses consist on the transportation and loading costs to deliver the sulphur to the buyer company, in cases of deliver to chartered ships the cost is about €10/ton, it is going to be assumed the same cost for this scenario;
- The price of the sulphur varies on the market, according to the refinery, in 2013, the price was situated approximately between €22/ton[2] ($30/ton) and €74/ton[2] ($100/ton);
- Based on the price variations 3 distinct price scenarios will be considered: scenario 1 = €22/ton; scenario 2 = €48/ton; and scenario 3 = €74/ton;
- The sulphur is currently being stored on the refinery, however, in the long term that is not a viable solution so for this financial analysis the avoid cost of having to send the sulphur to a landfill – €4,15/ton (Law Decree No 178/2006, 2006) will be considered;
- The difference between the amount of granulated sulphur produced and sold by the refinery in 2012, was approximately 434 ton and the refinery also had an additional 9158 ton stored by the end of 2012.(Galp Energia, 2012).
- For this financial analysis we will consider a scenario where those 434 ton are sold yearly together with the additional 9158 ton equally separated during the 10 year period (around 916 ton/year) with a total of 1350 ton sold per year.

<u>€22/ton scenario</u>

Table 4 - Financial analysis of the sulphur exchange in a €22/ton scenario.

CATEGORY	Period (years)				
	1	2	3	4	5 - 10
REVENUES (€)					
Sulphur sales	29704	29704	29704	29704	178226
Avoided storage costs	5644	5644	5644	5644	33863
TOTAL REVENUES	35348	35348	35348	35348	212089
COSTS (€)					
Transportation & Loading	13502	13502	13502	13502	81012
TOTAL COSTS	13502	13502	13502	13502	81012

$$\frac{Benefits}{Costs}\ Ratio = \sum\left(\frac{Revenues}{Costs}\right) = \frac{353482}{135020} = 2{,}618$$

[2]$1 = €0.736973985

€48/ton scenario

Table 5 - Financial analysis of the sulphur exchange in a €48/ton scenario.

CATEGORY	Period (years)				
	1	2	3	4	5 - 10
REVENUES (€)					
Sulphur sales	64810	64810	64810	64810	388858
Avoided storage costs	5644	5644	5644	5644	33863
TOTAL REVENUES	70453	70453	70453	70453	422721
COSTS (€)					
Transportation & Loading	13502	13502	13502	13502	81012
TOTAL COSTS	13502	13502	13502	13502	81012

$$\frac{Benefits}{Costs}\ Ratio = \frac{704534}{135020} = 5{,}218$$

€74/ton scenario

Table 6 - Financial analysis of the sulphur exchange in a €74/ton scenario.

CATEGORY	Period (years)				
	1	2	3	4	5 - 10
REVENUES (€)					
Sulphur sales	99915	99915	99915	99915	599489
Avoided storage costs	5644	5644	5644	5644	33863
TOTAL REVENUES	105559	105559	105559	105559	633352
COSTS (€)					
Transportation & Loading	13502	13502	13502	13502	81012
TOTAL COSTS	13502	13502	13502	13502	81012

$$\frac{Benefits}{Costs}\ Ratio = \frac{1055586}{135020} = 7{,}818$$

The results obtained in this financial analysis will be further discussed on section 5.3. of this thesis.

5.2.2. Water

5.2.2.1. Screening

The screening methodology is now going to be applied to the case of a cooling water exchange between the refinery and the power plant.

Regulatory context

		3		

Not favorable Highly Favorable

There is no legislation stopping this exchange from taking place. The cooling water after being used in the refinery process is usually discharged without treatment.

Geographic proximity

				5

Not favorable Highly Favorable

The oil refinery and the power plant are collocated companies, so the geographic distance between them is much less than the average 30km stated in the literature. This way, the close proximity between the two industries should be a driver for the exchange.

Technical viability

		3		

Not favorable Highly Favorable

This exchange should be technically viable because there are documented case studies of similar exchanges taking place, in Kalundborg for example.

Capital availability

		3		

Not favorable Highly Favorable

This exchange may require a considerable investment by the refinery, however and since Galp Energia is a major firm, if the exchange proves to bring economic profit there should be no issue regarding capital availability.

Payback period

	2			

Not favorable Highly Favorable

Based on the similar case presented in the literature – Kalundborg – the payback period is estimated to be around 5 years.

Virgin resource use avoided

			4	

Not favorable Highly Favorable

Since this considered water exchange will consist of substituting the water input for the process in the power plant for the cooling water from the oil refinery, the virgin water input for the power plant is avoided.

Waste re-use/recycling promoted

		3		

Not favorable Highly Favorable

In this purpose exchange this parameter does not apply.

Firms willingness to cooperate

			4	

Not favorable Highly Favorable

The oil refinery and the power plant have a good relationship (Dias, 2013) so if the project proves to be beneficial, both the industries would be willing to cooperate.

Overall perception of risks

	2			

Not favorable Highly Favorable

The power plant future can be the greatest risk concerning this exchange. There are rumors that the power plant may not continue operating for many more years. These rumors are based on the fact that this is a coal thermal power plant and due to continuously stricter legislation on carbon emissions. This fact could pose a major risk if the power plant were to cease its operation before the payback period of the investment made.

The overall result of the screening evaluation of the cooling water exchange is a score of 29 like is shown on Table 7. With this result being higher than 27 the exchange is considered promising and will be subject of a life cycle assessment and a financial analysis.

Table 7 - Cooling water exchange screening results

Parameters	Score
Regulatory context	3
Geographic proximity	5
Technical viability	3
Capital availability	3
Payback period	2
Virgin resource use avoided	4
Waste re-use/recycling promoted	3
Firms willingness to cooperate	4
Overall perception of risks	2
Total	**29**

5.2.2.2. Life cycle analysis

The LCA will be made considering the flows of a scenario where oil refinery and the power plant exchange cooling water (Figure 18) and one in which they do not (Figure 17).

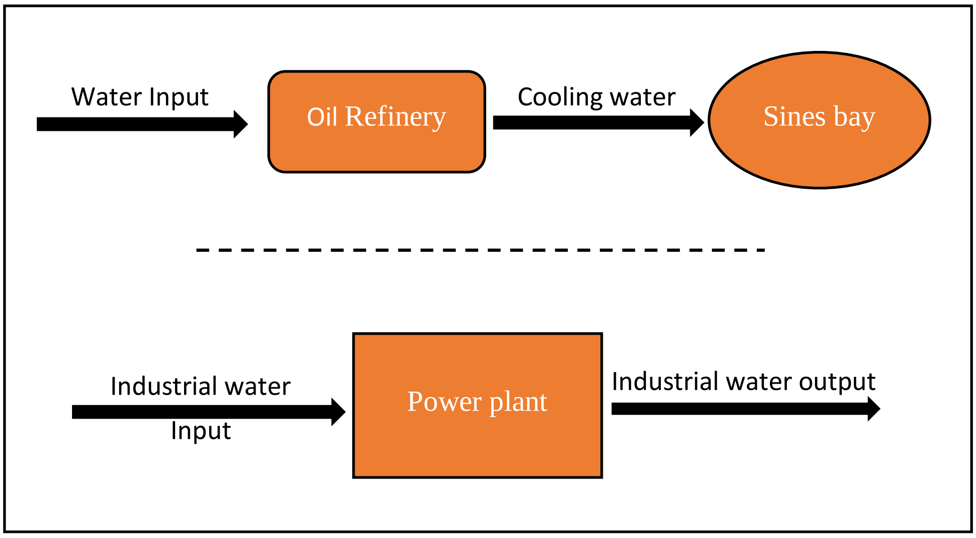

Figure 17- Resource flows of scenario without the water exchange.

The European Comission (2010), states that the "water use" indicator in LCA is a complex one due to the various sources that water can have, with some being renewable (e.g. sea water) and some not renewable (e.g. fossil/deep groundwater) (European Comission, 2010). It recommends that the water input to be differentiated in (European Comission, 2010): surface freshwater; renewable groundwater; fossil/deep groundwater; and sea water.

In the scenario without the water exchange the water input to the oil refinery is 92% from the network (surface freshwater) and the remaining 8% are groundwater. After being used the cooling water is discharged in to the sea. In the case of the power plant, despite the author's attempts, the company did not provide information about their water input. Due to this fact we can only assume that the input is probably a mix of surface water and groundwater like in the refinery, even though the percentages of each may differ.

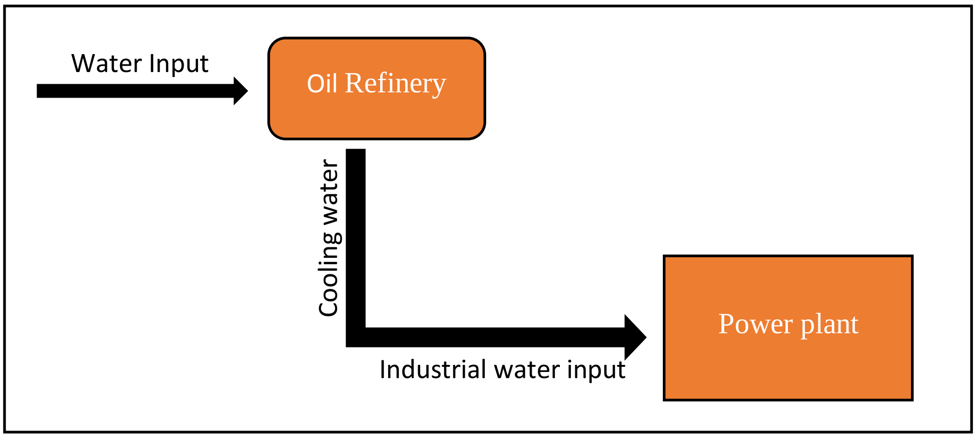

Figure 18 - Resource flows of scenario considering the water exchange.

In a scenario where the water exchange takes place the cooling water from the refinery, is provided to the power plant as a substitute for their industrial water input. Since the volume of cooling water from the refinery is much more than the power plant industrial water input only part of the cooling water could be exchanged. We are going to assume a scenario where the cooling water will substitute the total volume of the industrial water input by the power plant which is of approximately 2 909 828 m^3. In this scenario where the exchange takes place, 2 909 828 m^3 of surface freshwater and groundwater (without knowing the exact percentages of each) would be saved.

5.2.2.3. Financial analysis

The financial analysis is going to be made from the oil refinery perspective and the following aspects were considered:

- Income is represented by the cooling water sold to the power plant by the refinery;
- The expenses consist of expenditure of the investment and the cost of acquiring the cooling the water;
- The investment is assumed to be equally shared by both companies involved in the exchange and the discount rate considered will be equal to 0;
- The price of the cooling water from the refinery is linked to the price of surface water by a 50% discount;

- Based on a similar project on the Kalundborg case study, and after the prices actualization for 2012[3], the investment necessary for the exchange to happen is estimated to be of approximately € 217 000[4] by each of the companies involved;
- The cooling water has a total cost of 0,43292 €/m^3 for the refinery;
- The industrial water for the power plant, without specific treatment in the power plant, is assumed to have the same cost as the refinery cooling water since it is the same provider.

Table 8 - Financial analysis of the water exchange.

CATEGORY	Period (years)				
	1	2	3	4	5 - 10
REVENUES (€)					
Cooling water transaction	629861	629861	629861	629861	3779168
TOTAL REVENUES	629861	629861	629861	629861	3779168
COSTS (€)					
Investment necessary	217000	0	0	0	0
TOTAL COSTS	217000	0	0	0	0

$$\text{Payback period} = \frac{217000}{629861} = 0{,}35 \text{ years}$$

The results obtained in this financial analysis will be further discussed on the following section of this thesis.

5.3. DISCUSSION OF THE RESULTS

Through an analysis of the case study two potential new synergies were found, a sulphur exchange and a water exchange. After this findings both of the synergies were subject to an environmental and an economic evaluation.

In the case of the sulphur exchange, the environmental evaluation through a LCA demonstrated that the new scenario considered, where the synergy takes place, had a better environmental performance when compared to the current scenario. The results showed that in the case of the sulphuric acid being transported by sea from China CO_2 equivalent emissions were of 787 tons per year, while as in it being transported by road from a location near the refinery were of 318 tons, a difference of 469 tons of CO_2 equivalent emissions per year. Furthermore in the case where

[3] Actualization of 2 000 000 DKK made from 1987 to 2012 using GDP (Gross Domestic Product) deflator of The World Bank data for Denmark
[4] €1 = 7,4062 DKK

it is transported from China by sea an additional transport from the sea port to the final destinations would be required, adding even more CO_2 equivalent emissions per year to this scenario. It is safe to say that the carbon footprint, at least in what transport is concerned, is much smaller in a scenario where this potential new synergy takes place. For a complete and thorough LCA more data and a more complex software would be required.

In terms of economic evaluation this potential sulphur exchange also showed to be attractive with a benefit-cost ratio superior to one in every sulphur price scenario evaluated. One major contributor to this results is the fact that this potential exchange would not require any additional investment by the refinery. The higher the price considered in the scenario, the higher the benefit-cost was. This is due to the fact that costs are not related with price but with quantity. In this way, for all the scenarios considered the most beneficial is the scenario where the price is set at €74/ton, even though it is important to note that the exchange proves to have more benefits then costs in all the scenarios considered.

Passing on to the water exchange, the environmental evaluation showed that in a scenario where the synergy takes place around 2 909 828 m^3 of water would be re-used. This reutilization would mean savings in both surface freshwater and groundwater, even though the exact volume of each source was not disclosed. This environmental results would have additional value if those volumes were known but, unfortunately, due to reasons beyond the control of the author of this thesis those were not possible to obtain.

The financial analysis of this exchange also showed very promising results. The payback period for the investment made on the first year is estimated to be less than a year, even if the refinery were to make the totality of the investment instead of it being equally divided between the synergy partners the payback period would be still less than a year. The refinery has a revenue of 629 861 € per year while the power plant saves the exact same amount by getting the water from the refinery instead of the water network. Considering that both the refinery and the power plant use groundwater the savings can be even higher due to all the costs associated with groundwater such as energy consumption, pumping equipment maintenance, groundwater quality monitoring, etc. It is important to note that additional investment may be required on the power plant side to treat the water according to the parameters necessary for all its uses.

Based on the results obtained, both the sulphur and the water exchange seem to have a lot of potential. In terms of LCA a deeper analysis with more data and tools available would be more desirable. In the case of the sulphur exchange it may not prove to be an easy task to convince a sulphuric acid company to move to the Sines region because like Sterr and Ott (2004) stated most companies do not like to move and expect some compensation if they do. In what concerns the water exchange, the best thing would be for both companies involved in the potential synergy to discuss this synergy among themselves. It is also recommendable that the companies assess the actual investment necessary for the synergy to become a reality since the investment in the financial analysis was purely based on a case study on a different country with a similar project and so it may vary.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The overall aim of this research project was to find and evaluate new potential exchanges in light of IS for the Sines oil refinery case study. For that purpose a methodology was developed and two new potential exchanges were found and evaluated with the results of the methodology application shown and discussed in previous sections of this thesis.

Despite the results obtained, during this research the author faced some barriers that were already mentioned in this thesis on the literature review of the barriers for the implementation of the IS concept application. The main barrier found was the necessity of scale and diversification of the industrial sector in the region and country where the IS concept was trying to be implemented. It was concluded that the industrial sector in Portugal lacks precisely that scale and diversity, without this diversity synergies fail to be established simply due to the fact of not having complementary industries for a successful input-output matching. One possible reason for this to happen is the fact that Portugal is a relatively small market, an example of this is the inexistent presence of a sulphuric acid producer in the entire country.

One possible way of fighting this lack of diversity of close-by industries is by creating eco industrial parks (EIP's). An embracing definition of EIP was given by Martin et al. (1996) which states that an EIP is a "*community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaborating in the management of environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only*." EIP follow IE principles and this community of companies work together to achieve an industrial ecosystem. This industrial ecosystem is a comparison with natural ecosystems where there is virtually no waste, the waste products from one process are integrated in another process. In an ideal EIP all the industries and companies in the community complement each other. It is important to note, though, that the planning of an EIP project is a difficult task and that most planned EIP's experiences have not been very successful (Gibbs & Deutz, 2007).

Another barrier found during the course of this research was the difficulty in acquiring information. Some companies, even though it is important to state that not all of them, were not very open about giving information concerning their production processes and/or prices, despite the author's efforts made through e-mails and/or telephone to get that information. This is a case of both an information and motivational barrier where the companies do not have enough trust to provide the information needed for a better link between supply and demand. In this way, it is important to have a facilitator of IS, like it is called in the literature, someone who is independent and impartial and that can engage the different companies into cooperating (Costa, 2011). In this research this part was made by the author of this thesis but, like previously stated, not always in a successful manner.

As future developments the author recommendations go towards assessing the real investment necessary for the water exchange to become a reality and for the companies involved to engage in conversations towards this possibility of water substitution. The author hopes for a positive reply, in a near future, from the fertilizer production company towards incorporating the elemental sulphur in their production process. The author recommends that future research is made towards evaluating and uncovering the IS potential of the entire Sines industrial area. For this purpose the creation of a council to facilitate the cooperation between the different industries in the Sines industrial area would be recommended. Lastly, the author would recommend the application of the methodology developed, in further case studies to better test its potential.

REFERENCES

Agarwal, A. (2011). Ecological modernisation and the development of the UK's green industrial strategy: the case of the UK National Industrial Symbiosis Programme. *OpenAIR@RGU [online]*. Retrieved from http://openair.rgu.ac.uk

AICEP. (2013, August). *AICEP Global Parques*. Retrieved from http://www.globalparques.pt/subpagezils.php?cd_pagina=223

Allenby, B. (2006). The ontologies of industrial ecology? *Progress in Industrial Ecology - An International Journal, 3*, 28-40.

Allenby, B. R. (1999). *Industrial Ecology: Policy Framework and Implementation.* Prentice-Hall: Upper Saddle River.

Bebbington, J. (2001). Sustainable development: a review of the international development, business and accounting literature. *Accounting Forum, 25 (2)*, 128-157.

Boons, F., Spekkink, W., & Mouzakitis, Y. (2011). The Dynamics of Industrial Symbiosis: a proposal for a conceptual framework based upon a compreehensive literature review. *Journal of Cleaner Production, 19*, 905-911.

Brand, E., & de Bruijn, T. (1999). Shared Responsability at the Regional Level: the building of sustainable industrial estates. *European Environment, 9*, 221-231.

Centre of Excellence in Cleaner Production. (2007). *Regional Resource Synergies for Sustainable Development in Heavy Industrial Areas: An Overview of Opportunities and Experiences.* Perth: Curtin University of Technology.

Chertow, M. (2000). Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and Environment, 35*, 313-337.

Chertow, M. (2007). "Uncovering" Industrial Symbiosis. *Journal of Industrial Ecology, 11 (1)*, 11-30.

Chertow, M. R., & Lombardi, D. R. (2005). Quantifying Economic and Environmental Benefits of Co-Located Firms. *Environmental Science & Techonology, 17*, 6535-6541.

Chertow, M. R., Ashton, W. S., & Espinosa, J. C. (2008). Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. *Regional Studies, 42:10*, 1299-1312.

Costa, I. (2011). The Challenge of Industrial Symbiosis. *Ph.D Thesis*. Universidade Técnica de Lisboa.

Desrochers, P. (2000). Market processes and the closing of industrial loops. *Journal of Industrial Ecology, 4 (1)*, 29-43.

Desrochers, P. (2004). Industrial symbiosis: the case for market coordination. *Journal of Cleaner Production, 12*, 1099-1110.

Dias, S. (2013, April 22). Oral Communication.

Ehrenfeld, J., & Gertler., N. (1997). Industrial ecology in practice. *Journal of Industrial Ecology, 1*, 67 -79.

Erkman, S. (1997). Industrial ecology: an historical view. *Journal of Cleaner Production, 5*, 1-10.

European Comission. (2008). *Guide to COST-BENEFIT ANALYSIS of investment projects.*

European Comission. (2010). *International Reference Life Cycle Data System (ILCD) handbook : General guide for Life Cycle Assessment - Detailed guidance.* Luxembourg: Publications Office of the European Union.

Frosch, R. A., & Gallopoulos, N. (1989). Strategies for Manufacturing. *Scientific American, 261(3)*, 144-152.

Galp Energia. (2012). *Sines Refinery Operational Report.*

Galp Energia. (2013, August). Retrieved from http://www.galpenergia.com/PT/agalpenergia/os-nossos-negocios/Refinacao-Distribuicao/ARL/Refinacao/RefinariaSines/Paginas/Refinaria-de-Sines.aspx

Gibbs, D., & Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *Journal of Cleaner Production, 15*, 1683-1695.

GTZ. (n.d.). Development of Sustainable Industrial Estates. GTZ. Retrieved from http://www2.gtz.de/dokumente/bib/05-0194.pdf

GTZ/IEAT. (2001). The Economic and Environmental Status of Map Ta Phut Industrial Estate. Bangkok, Thailand: GTZ and Industrial Estates Authority of Thailand.

Harris, S. (2004). Drivers and Barriers to Industrial Ecology in the UK. *PhD Thesis*. University of Edinburgh.

Harris, S. (2007). The Potential Role of Industrial Symbiosis in Combating Global Warming. *International Conference on Climate Change.* Hong Kong.

Harris, S., & Pritchard, C. (2004). Industrial Ecology as a learning process in business strategy. *Progress in Industrial Ecology, 1 (1/2/3)*, 89-111.

Harrisson, P. (n.d.). Global Sulphur Market Outlook. CRU. Retrieved from http://www.chemico-group.com/ru/images/stories/conf_sulf/world_2017.pdf

Heeres, R., Vermeulen, W., & de Walle, F. (2004). Eco-industrial park initiatives in the USA and The Netherlands: first lessons. *Journal of Cleaner Production, 12*, 985-995.

Homchean, K. (2004). Case Study Map Ta Phut Industrial Estate. *Partnership for the Future (2nd International Conference & Workshop for Eco-Industrial Development)*. Bangkok, Thailand: Eco-Industrial Estates Network Asia.

International Standard ISO 14040. (1997). Environmental management - Life cycle assessment - Principles and framework.

International Standard ISO 14041. (1998). Environmental management - Life cycle assessment - goal and scope definition and inventory analysis.

International Standard ISO 14042. (2000). Environmental management - Life cycle assessment - life cycle impact assessment.

International Standard ISO 14043. (2000). Environmental management - Life cycle assessment - life cycle interpretation.

Jacobsen, N. (2006). Industrial Symbiosis in Kalundborg, Denmark : A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology, 10*, 239-256.

Jacobsen, N., & Anderberg, S. (2004). Understanding the Evolution of Industrial Symbiotic Networks: The case of Kalundborg. In J. C. Berg, & M. C. Jansen, *Economics of Industrial Ecology* (pp. 313-336). Cambridge: MIT Press.

Jelinski, L. W., Graedel, T. E., Laudise, R. A., McCall, D. W., & Patel, C. K. (1992, February). Industrial ecology: Concepts and approaches. *National Academy of Sciences, 89*, 793-797.

Jensen, P. D., Hellawell, E. E., Bailey, M. R., & Leach, M. (2011). Quantifying 'geographic proximity': Experiences from the United Kingdom's National Industrial Symbiosis Programme. *Resources, Conservation and Recycling, 55*, 703-712.

Kalundborg Symbiosis. (2013). Retrieved from Kalundborg Symbiosis: http://www.symbiosis.dk/

Klöpffer, W. (1997). Life Cycle Assessment: From the Beggining to the Current State. *Environmental Science & Pollution Research, 4 (4)*.

Law Decree No 178/2006. (2006, September 5th). Retrieved from http://dre.pt/pdf1sdip/2006/09/17100/65266545.pdf

Lowe, E. (1997). Creating by-product resource exchanges: strategies for eco-industrial parks. *Journal of Cleaner Production, 5*, 57-65.

Martin, S. A., Weitz, K. A., Cushman, R. A., Sharma, A., & Lindrooth, R. C. (1996). *Eco-Industrial Parks: A Case Study and Analysis of Economic, Environmental, Technical, and Regulatory Issues.* Washington (DC): Office of Policy, Planning and Evaluation. U.S. Environmental Protection Agency.

Mattila, T. J., Pakarinen, S., & Sokka, L. (2010). Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input - Output Life Cycle Assessment. *Environmental Science & Technology, 44*, 4309-4314.

Mattila, T., Lehtoranta, S., Sokka, L., Melanen, M., & Nissinen, A. (2012). Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbiosis. *Journal of Industrial Ecology, 16*, 51-60.

Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. *Journal of Cleaner Production, 12*, 967-983.

Pinyochatchinda, S., & Walsh, J. (2012). Map Ta Phut as an Exemplar of the Industrial Estates of Thailand. *Journal of Social and Development Sciences, 3*, 6-15.

PRé Consultants. (2008). SimaPro Database Manual: Methods library.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., . . . Pennington, D. W. (2004). Life cycle assessment - Part 1: Framework, goal and scope definition, inventory analysis, and apllications. *Environment International, 30*, 701-720.

Sea Rates. (2013). *Sea-Rates.com*. Retrieved from http://www.searates.com/reference/portdistance/

Sinclair Knight Merz. (2002). Kwinana Industrial Area Economic Impact Study: An example of industrial interaction. Perth, WA, Australia.

Sokka, L., Lehtoranta, S., Nissinen, A., & Melanen, M. (2011). Analyzing the Environmental Benefits of Industrial Symbiosis: Life Cycle Assessment Applied to a Finnish Forest Industry Complex. *Journal of Industrial Ecology, 15*, 137-155.

Sterr, T., & Ott, T. (2004). The industrial region as a promising unit for eco-industrial development - reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production, 12*, 947-965.

The Sulphur Institute. (2013, September). *The Sulphur Institute*. Retrieved from http://www.sulphurinstitute.org/learnmore/sulphur101.cfm

Tudor, T., Adam, E., & Bates, M. (2007). Drivers and Limitations for the sucessful development and functioning of EIPs (eco-industrial parks): A literature review. *Ecological Economics, 61*, 199-207.

United States Census Bureau. (2013, May). Retrieved from http://www.census.gov/2010census/popmap/ipmtext.php?fl=72

van Beers, D. (2008). *Capturing Regional Synergies in the Kwinana Industrial Area: A Status Report.* Centre for Sustainable Resource Processing, Perth, WA, Australia.

van Beers, D. (2009). Application of the Cleaner Production Framework to the Development of Regional Synergies in Heavy Industrial Areas: A Case Study of Kwinana (Western Australia). *Ph.D Thesis*. Curtin University of Technology.

van Beers, D., Corder, G., Bossilkov, A., & van Berkel, R. (2007). Industrial Symbiosis in the Australian Minerals Industry: The Cases of Kwinana and Gladstone. *Journal of Industrial Ecology, 11*, 55 - 72.

van Berkel, R., van Beers, D., & Bossilkov, A. (2006). Regional Resource Synergies for Sustainable Development: The Case of Kwinana. *Materials Forum, 30*, 176-187.